OPERATIONS ANALYSIS OF FLEET BATTLE EXPERIMENTS USING THE BATTLESPACE INFORMATION WAR METHODOLOGY

PRELIMINARY REPORT

Donald P. Gaver
Patricia A. Jacobs
Steven E. Pilnick

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The Institute for Joint Warfare Analysis
Naval Postgraduate School
Monterey, California

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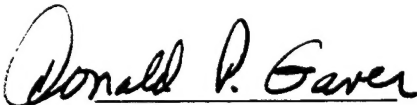## NAVAL POSTGRADUATE SCHOOL
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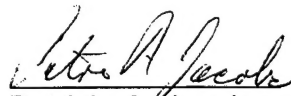Superintendent   Provost

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Authors:

Donald P. Gaver   Patricia A. Jacobs   Steven E. Pilnick

Reviewed by: Released by:

GORDON E. SCHACHER   DAVID W. NETZER
Director   Associate Provost and
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13. ABSTRACT (maximum 200 words)

This report outlines an approach for quantitative operations analysis of aspects of Fleet Battle Experiments (FBEs) using the methodology underlying the Battlespace Information War (BAT/IW) analytical tool. The general approach of this analysis methodology is to focus on a specific experimental initiative from one or more FBEs, such as Time Critical Targeting (TCT). BAT/IW models are then tailored to the experimental situation using actual data obtained from one or more experiments and the experiment systems architecture. After the models and actual data are reconciled, further analysis tasks are undertaken, such as predictions of the effects of attack intensity, and/or of C4ISR response time reduction. BAT/IW modeling helps analyze and understand the system-level impact of sensor data quality, including timeliness, as one contributor to total operation/campaign success. BAT/IW modeling also accounts for the latency involved in processing information, including communications delays, decision time, waiting, etc. An example is developed to show how operational data obtained during FBE Foxtrot can be quantitatively analyzed to indicate important sensitivities.

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EXECUTIVE SUMMARY

Overview

This report outlines an approach for quantitative operations analysis of aspects of Fleet Battle Experiments (FBEs) using the methodology underlying the Battlespace Information War (BAT/IW) analytical tool. Key features of this approach are the following:

(1) Quick model set-up.

(2) Very fast computer execution

(3) High-level insights.

Approach

The general approach of this analysis methodology is to focus on a specific experimental initiative from one or more FBEs, such as Time Critical Targeting (TCT). Battlespace Information War (BAT/IW) models are then tailored to the experimental situation using actual data obtained from one or more experiments, incorporating the experiment systems architecture. After the models and actual data are reconciled, further analysis tasks are undertaken.

Objectives

The objectives of operational, model-based analysis of FBE, and other data are several.

(a) To supply planners and analysts with quick-turnaround, high-level (although low resolution) information on actual and prospective FBE outcomes.

(b) To evaluate Measures of Operational Effectiveness (summary guides to understanding).

(c) To evaluate the projected effect of new Blue (and also Red) capability (added bandwidth = communication speed = lower/reduced lateness, *and/or* new sensor configurations and capabilities, *and/or* new weapons, and faster, differently managed but possibly vulnerable communication links on Blue force effectiveness (weapons on target vs. weapons expended).

(d) To evaluate the projected effect of revised CONOPS by both sides, with attention to risk and crisis control.

Analysis Tool: The Battlespace Information War Model (BAT/IW)

There are at least two aspects of warfare that are addressed using relatively simple tools in BAT/IW.

(a) BAT/IW modeling helps analyze and understand the system-level impact of sensor data quality, including timeliness, as one contributor to total operation/campaign success.

(b) BAT/IW modeling accounts for the latency involved in processing information, including communications delays, decision time, waiting, etc. Such latency can strongly, and negatively, influence success of Time-Critical Targeting.

Example: Analysis of FBE Foxtrot Data Using BAT/IW

An example shows how operational data obtained during FBE Foxtrot can be quantitatively analyzed. The BAT/IW modeling concepts can be utilized to explore other alternatives: different patterns of Red threats (e.g. more time-concentrated or surge-like, extensive use of decoys, various air defense CONOPS), *and* different Blue force sizes and types. *Note*: these additional steps are not carried out here, but will be the topics of future work. In FBE Foxtrot, data collected arises from time critical targets (TCTs) that are nominated to the LAWS (Land Attack Weapon System). Nominated target images are simultaneously sent to JTW (Joint Targeting Workstation). At the JTW stage an operator (currently human) processes the images: those images are classified and mensurated, i.e. given geographical coordinates (which of course are subject to error, which ultimately degrades weapon effectiveness). When this step is complete, the potential target images become the responsibility of LAWS to assign to weapons, and possibly to specific platforms. The stages before nomination and after LAWS assignment are not analyzed in this example, since data were not available.

During FBE Foxtrot, there were 176 TCTs nominated, of which 93 were fired upon. Thus, 83 of the targets were not fired upon. Of these 83 targets, 47 were not fired upon due to deficiency of time, target information, or resources. The remaining 36 targets were not fired upon for other causes.

In order to analyze available data we model the entire LAWS and JTW (sub) system (here called a central processing (CP) system, actually, a part of such a system) as a single-server queuing process with losses (caused by targets that move or hide, or otherwise foster inability to mensurate, hence qualify a target). The "single server" delay is assumed dominated by human operators: those who provide mensuration, and the LAWS-shooter weapons assignment delay. Communications delays are implicitly included. The presently available data provide no information that allows separation of stages (mensuration and firer classification, and weapons-target pairing).

We consider three models for the CP delays, with mean times estimated from FBE Foxtrot data, that incorporate the information that of the 83 targets that were not fired upon, 36 targets were not fired upon for causes other than deficiency of time, etc. A question that the analysis showed to be important is: when were those 36 targets discovered, and when were they eliminated? The three models account for different possibilities.

An interesting insight obtained from the analysis of this example is recognition of the effect that the presence of the 36 targets which were not fired upon because of reasons other than deficiency in time, etc. can have on the performance of the CP system. The results show that the amount of CP resources that these 36 targets consume has a large effect on the ability to fire missions against time critical targets. The fraction of targets for which a firing command is given is largest for Model III in which the targets are identified *almost as soon as they are nominated* as not being targetable. This is an ideal, optimistic special case, but is quantified for illustration of the best that can be done. The other cases are more realistic, but teach the same lesson. It is clearly important for the CP to identify these targets as early as possible and remove them from consideration before they consume further CP resources.

1. INTRODUCTION

Overview

This report outlines an approach for quantitative operations analysis of aspects of Fleet Battle Experiments (FBEs) using the methodology underlying the Battlespace Information War (BAT/IW) analytical tool; see Gaver and Jacobs (2000). Key features of this approach are the following:

(1) <u>Quick model set-up</u>. Once an FBE situation or systems architecture is described, models can be tailored for BAT/IW analysis very quickly. Initial modeling might take a few hours, followed by a few hours to enter the model on a computer, followed by a few hours to verify that the model is performing as intended. The total elapsed time to set up a new situation is typically no more than a few days. Variation of basic parameters, such as target arrival rates and patterns, takes minutes to hours.

(2) <u>Very fast computer execution</u>. BAT/IW models are built with systems of mathematical equations that can be solved very quickly in a computer. On a typical desktop PC, runs of BAT/IW expected value models put graphical results on the computer screen in milliseconds. This very fast execution is particularly well suited for "what-if" analysis by operators as well as analysts.

(3) <u>High-level insights</u>. BAT/IW modeling seeks to provide a basis for high-level insights through low-resolution models. BAT/IW looks at overall trends in the battlespace rather than focusing on individual unit interactions. It is also possible to plug system-level performance data obtained from high-resolution models into BAT/IW for subsequent analysis at the operational level.

The following paragraphs in this section summarize the general approach and objectives of this work. Section 2 further describes BAT/IW. An introductory example, using data from FBE Foxtrot, appears in Section 3.

Approach

The general approach of this analysis methodology is to focus on a specific experimental initiative from one or more FBEs, such as Time Critical Targeting (TCT). Battlespace Information War (BAT/IW) models are then tailored to the experimental situation using actual data obtained from one or more experiments and the experiment systems architecture. After the models and actual data are reconciled, further analysis tasks are undertaken. For instance, *first*, the models and data are exercised to extract greater understanding about what was observed. *Second*, "what-if" analysis is performed to expand the experimental results to a wider range of parameter inputs, e.g. by increasing the numbers of enemy (Red) candidate targets, or speeding up (or slowing down) target processing. *Third*, insights are sought which suggest development of particular tactics, techniques, or procedures, and/or specific needs for further live experimentation and *operational data collection* during subsequent FBEs. *Fourth*, exploratory analysis is conducted of prospective architectures that might involve spatially dense sensor systems and a "flat" information--weapon-target-pairing--targeting system.

Objectives

The objectives of operational, model-based analysis of FBE, and other data are several.

(a) To supply planners and analysts with quick-turnaround, high-level (although low resolution) information on actual and prospective FBE outcomes: data explanation and military-operational significance, by consideration of basic mechanisms of operational data creation and flow. The accuracy of such depends on an adequate model representation of the data obtainable during an FBE. A difficulty is that *observational* data obtained from at least some FBEs is of unknown completeness and quality. The BAT/IW analytical methodology can supply sensitivity tests of alternative interpretations of *partially observed and reported operational* data.

(b) To evaluate Measures of Operational Effectiveness (summary guides to understanding). The capability to answer such what-if information as

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- The effect on operational data flow, (message traffic, e.g. numbers of potential Red targets engaged, and Blue (own) response capability) of increasing (e.g. doubling) and time-concentrating enemy forces.
- The projected effect of various forms of enemy deception, as by use of decoys. Such Information War (IW) issues have been stressed in BAT/IW; see Gaver and Jacobs (2000).

(c) To evaluate the projected effect of new Blue (and also Red) capability (added bandwidth = communication speed = lower/reduced lateness), and/or new sensor configurations and capabilities, and/or new weapons, and faster, differently managed but possibly vulnerable communication links on Blue force effectiveness (weapons on target vs. weapons expended). Eventually, Blue platform loss rate.

(d) To evaluate the projected effect of revised CONOPS by both sides, with attention to risk and crisis control.

2. ANALYSIS TOOL: THE BATTLESPACE INFORMATION WAR MODEL (BAT/IW) AND ITS EMPHASIS

There are at least two aspects of warfare that are addressed, initially using relatively simple tools (but not necessarily always or forever), in BAT/IW.

(a) Sensor and other (HUMINT, SIGINT, ELINT…) data collected on enemy force levels and types, maneuver and behavior, etc., are subject to *detection delay* and *classification error*. This classification error emphatically includes that of BDA.

- ***BAT/IW modeling helps analyze and understand the system-level impact of sensor data quality***, including timeliness, as one important contributor to total operation/campaign success. Tradeoff analyses can be conducted of interlinked interactive system components, such as Information Acquisition, Communications, Weapons-Target Pairing, and BDA.

(b) Under current architectures (referred to here as *Central Processor* (CP)), "sensor" data passes to, and through (if track is not lost), a sequence of subprocessors that prepare it for assignment to weapons systems, and even to specific platforms. The choice of appropriate weapons systems is subject to target classification error, a topic treated in Gaver and Jacobs (2000).

- ***BAT/IW modeling accounts for the latency involved in these stage(s)***; latency of response to Time-Critical Targets seriously degrades or vitiates (and cumulatively and "nonlinearly" so) that response: a response that has been too slow, or mis-allocated, will have occupied CP attention needlessly, and thus handicapped response to subsequent target candidates. The effect tends to pyramid, allowing opportunity to Red. BAT/IW analysis can evaluate the capability of a given Blue CP architecture and CONOPS to respond to various Red threats. Some of this latency could be the result of unfavorable "surge" patterns of enemy (Red) activities. Such effects can be, and have been, portrayed using BAT/IW techniques.

3. EXAMPLE: ANALYSIS OF FBE FOXTROT DATA USING BAT/IW

We show how operational data obtained during FBE Foxtrot can be quantitatively analyzed. The BAT/IW model can be utilized to explore alternatives: different patterns of Red threats (e.g. more time-concentrated, extensive use of decoys, adoption of evasion and mobility techniques, various air defense CONOPS), *and* different Blue force sizes and types.

(a) Data

Appendix B of Gallup et al. (2000), (referred to as (G+) in what follows), presents data that arises from targets that are nominated to the LAWS (Land Attack Weapon System). Nominated target images are simultaneously sent to JTW (Joint Targeting Workstation). At the JTW stage an operator (currently human) processes the images: those images are classified and mensurated, i.e. given geographical coordinates (of course these are subject to

error, which ultimately degrades weapon effectiveness). When this step is complete, the potential target images become the responsibility of LAWS to assign to weapons, and to specific platforms. The stages before nomination and after LAWS assignment are not analyzed in the current example; appropriate data were unavailable.

(b) **Data and Model**

Appendix B of G+ presents data for the time from receipt of target nomination at LAWS (land attack weapon system) until firing at Red time-critical targets (TCT). There were 176 Red TCTs nominated, of which 93 were fired upon. Thus, 83 of the targets were not fired upon. Of these 83 targets, 47 were not fired upon due to deficiency of time, target information, or resources. The remaining 36 targets were not fired upon for other causes; see G+, pages 84-85 for description. We have *initially assumed* that these 176 targets arrived "uniformly at random" during 12-hour periods on 4 days, 12/5 through 12/8. Thus *provisionally*, the constant arrival rate is taken to be

$$\lambda = 176/(12*4) = 3.67 \text{ target nominations per hour.}$$

If desired, this can be allowed to define the mean of a stochastic arrival process, for instance Poisson. The present model is a "fluid approximation" to classical elementary queuing models. It is more general in that arrival rate, λ, can easily be made a function of time, $\lambda(t)$.

Figure 2 of Appendix B in G+ presents a histogram of the variable times from receipt of the target nomination at the LAWS server until weapon firing for those 61 targets for which this information could be obtained. In many cases the time at which the command "Fire When Ready" (FWR) was transmitted to the firer has been adopted as the firing time because of missing data; G+, p86. We will use time intervals in this histogram to represent the time from target nomination until the command FWR for the targets' total time in a central processor. Table 3 of G+ reports the median time of data in this histogram as 33 min. We consequently assume a median target time in the central processor of $0.55 = 33/60$ hours; this time includes both waiting time and service time. If one assumes an exponential distribution for this time, supported in steady-state by heavy traffic queuing theory, the median

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corresponds to the mean time between target (image) nomination until the command FWR of $W = 0.55/\ln(2) = 0.79$ hours. This mean delay time, W, is taken as *fixed* during what follows.

In order to analyze available data we model the entire LAWS and JTW (sub) system (here called a central processing (CP) system, actually a part of such a system) as a single-server queuing process with losses (caused by targets that move or hide, or otherwise foster inability to mensurate, hence qualify a target). The "single server" delay is assumed dominated by human operators: those who provide mensuration, and the LAWS-shooter weapons assignment delay. Communications delays are implicitly included. The presently available data provide no information that allows separation of stages (mensuration and firer classification, and weapons-target pairing).

We must utilize the semi-stochastic BAT/IW-style model to "read back" or *infer* the mean service time of the saturable, or increasingly lossy CP service system in the presence of increasing target candidate loads: each potential target is assumed subject to a loss rate, denoted ν, where the mean time "in queue" until loss is $1/\nu$. In practice, for present FBE Foxtrot the mean loss time is on the order of hours (2-4 perhaps). Note that there are other would-be targets that appear to transit (and load up) the CP stage but are finally evicted at the FWR stage.

A further set of data is the number of targets that enter the CP that were actually targeted during FBE F. Using our model(s), we can match those data (averages thereof) by choice of the service rate parameter, $\mu_E = 1/m_E$, having assumed an approximate loss rate, ν (e.g. 1 hour).

We consider 3 models for the CP delays, with mean *estimated from FBE F data*, that incorporate the information that, of the 83 targets that were not fired upon, 36 targets were not fired upon for causes other than deficiency of time, etc. The question is: when were they discovered and eliminated? We do models under differing circumstances.

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Model I: we assume that there is one loss rate that includes loss due to all causes. In Model I these 36 targets are lost *before* the stage at which the command FWR is given. Thus in Model I we assume that 93 commands to FWR are given.

Model II: we assume that the 36 targets not fired upon for other causes are not subject to loss and they are in the system until the point at which a command to FWR could have been given. Thus in Model II we will assume that 93+36=129 commands to FWR could have been given, a fraction of which are not given the command.

Model III: we assume that the 36 targets are identified *when they are nominated* as not being available for targeting at the end of the CP stage. Thus, in Model III there are 176-36 targets nominated which we will assume arrive at a constant rate over a 48-hour period at arrival rate 2.91 nominations per hour. In Model III we assume 93 commands to FWR are given. This is clearly the most optimistically biased assumption.

In Appendix A, a BAT/IW-style fluid model of the number of targets waiting or being served in a CP server with target losses is presented; the central processor here is LAWS and the JTW (Joint Targeting Workstation). The parameters of the model are the (possibly time dependent, but here assumed constant) arrival rate of target nominations to LAWS, the mean target loss time, denoted $1/v$, and the mean service/actual CP information processing time (mensuration, LAWS weapons assignment decisions, etc., until the command FWR is capable of being given) of a target once it has been nominated. Also presented is a differential equation for the time that a new target spends in the designated CP. The steady-state equation for the mean time a target spends in the central processor yields an equation for the mean target service time as a function of mean target loss time for a specified mean time between target nomination and the possible command to FWR.

Figure 1 displays the mean target service time versus the mean target loss time corresponding to a given mean time between target nomination and the command FWR of 0.79 hours for arrival rate $\lambda = 3.67$. The figure shows that the mean service time can be quite

sensitive to the mean target loss time, *given* that the mean delay time, $W = 0.79$. This figure depends upon "knowing" rate λ.

Arrival rate of tgts=3.67/hour
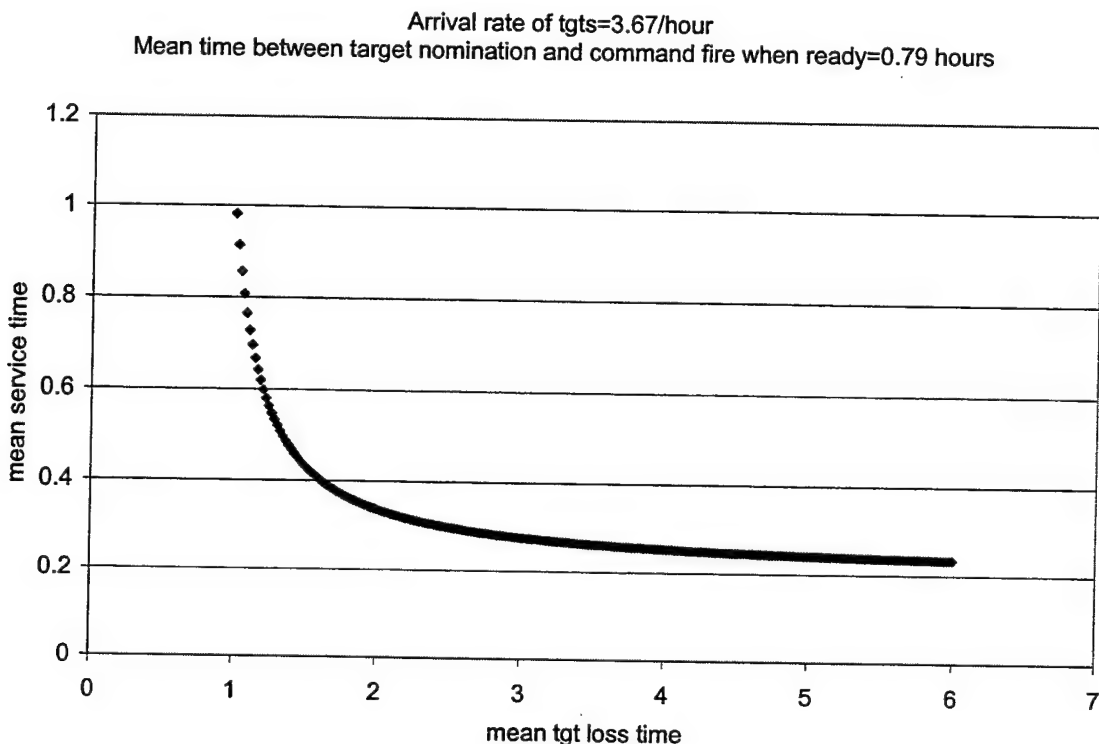Mean time between target nomination and command fire when ready=0.79 hours

Figure 1

In words, the same estimated mean delay time $W = 0.79$, which is here based on FBE Foxtrot data, can be achieved by, e.g. (1) a mean service time of $1/\mu \approx 0.6$ hour and a mean loss time of $1/v \approx 1$ hour *or* (2) a mean service time of $1/\mu \approx 0.35$ hour and a mean loss time of $1/v \cong 2$ hours; further combinations consistent with the curve are possible. However, the former case (1) allows many more targets to be lost than does the latter (2). Another observed summary allows specification of $1/\mu$ and $1/v$ parameters for the present data set.

Figure 2 displays the mean number of commands to FWR issued during the $12*4 = 48$ hour period obtained from solving the fluid model using the parameters: arrival rate 3.67/hour, and mean target loss times ($1/v$) and mean service times ($1/\mu$) found in Figure 1 (using mean time from target nomination to command to FWR equal to $W = 0.79$ hours).

The results displayed in Figure 2 show that the rate at which the command "fire when ready" can be transmitted is, as anticipated, very sensitive to the mean target loss time.

Mean Number of Commands to Fire when Ready made during 4 day period
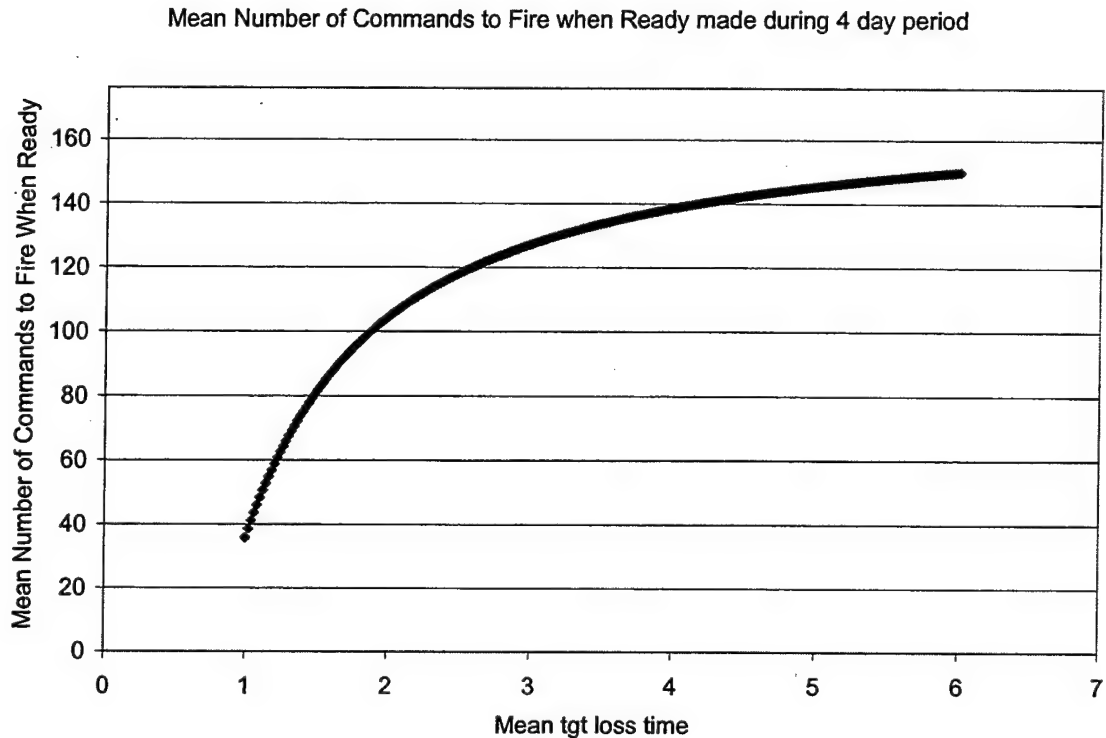
Figure 2

(c) Model I

In Model I the command FWR is assumed given for 93 targets out of the 176 targets nominated (see G+, p. 84). The fluid model shows that if the mean time between target nomination and the command FWR is $W = 0.79$ hours and 93 commands were given in the 48 hour period, then the mean target loss time, $(1/v)$, is about 1.7 hours and the mean service time by the central processor (LAWS and JTW) is about 0.38 hours $\approx$ 23 minutes, "on the average". This figure is at least roughly order-of-magnitude consistent with informed intuition. It can be used for further situational exploration and *analysis of operational alternatives* (AoOA, a subcategory of AoA, the analysis of alternatives of common reference).

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(c.1) AoOA: Sensitivity to Nomination Rate and Mean Service Time Variations for Model I

Table 1 presents the fraction of targets for which there is a command to FWR as the arrival rate and mean service time varies. The bold entry corresponds to the fraction of targets for which there is command FWR for the parameters determined from FBE F data. The alternative arrival rates are 0.5 times and 2 times the base arrival rate of 3.67 targets nominated per hour. The mean alternative service times are 0.5 times and 2 times the base mean service time of 0.38 hours.

Fraction of Targets for which a Command FWR is Issued

		Nomination rate λ(tgts per hour)		
		1.83	**3.67**	7.36
Mean	0.19	0.86	0.79	0.59
service time	**0.38**	0.69	**0.53**	0.32
m_E (hrs)	0.76	0.44	0.29	0.16

Table 1

A display of the fraction of targets for which a command of FWR is issued appears as Figure 3.

Fraction of tgts for which a command FWR is issued
The 36 targets that were not fired upon for reasons other than deficiency in time,
resources,etc are subject to same loss mechanism while in the system
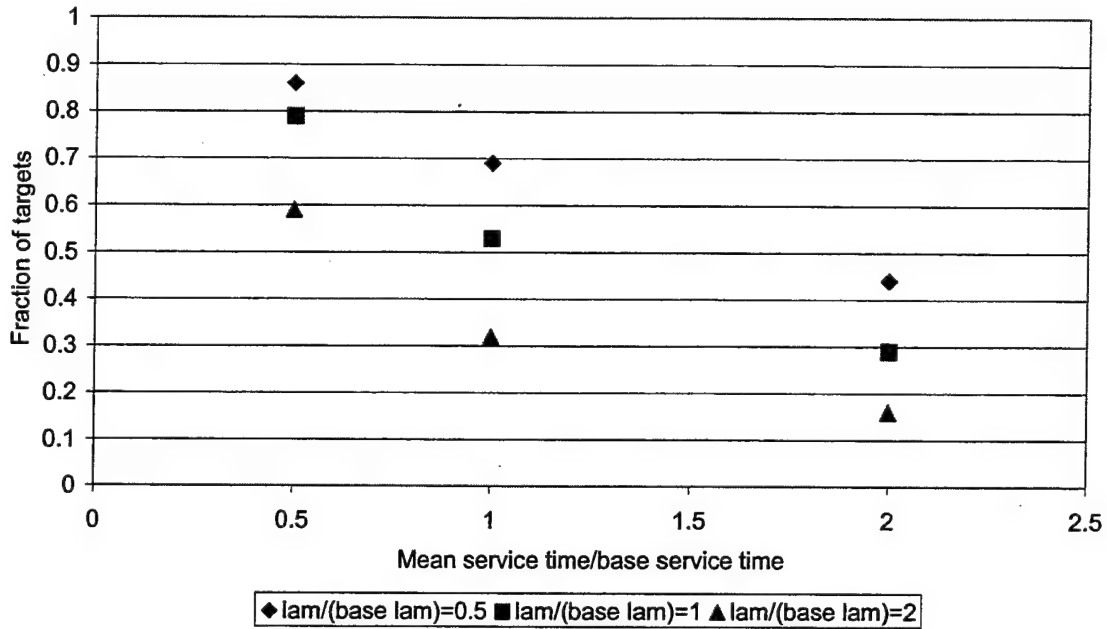
Figure 3

(d) Model II

We alternatively assume that the command FWR could be given for 129 targets out of the 176 targets nominated, but not all the commands are given (delete 36) at/just before the command FWR; see G+ pp. 84-85. The fluid model shows that if the mean time between target nomination and the command FWR is $W = 0.79$ hours and 129 commands could be given in the 48 hour period, then the mean target loss time, $(1/\nu)$, is about 3.1 hours and the mean service time by the central processor (LAWS and JTW) is about 0.27 hours $\approx$ 16 minutes, "on the average". However, in just the fraction 93/129=0.72 of these cases the command FWR was actually given.

(d.1) AoOA: Sensitivity to Nomination Rate and Mean Service Time Variations, 1

The table below presents the fraction of targets for which there is a command to FWR as the arrival rate and mean service time varies. The fraction is obtained by computing the mean number of targets for which the command FWR would have been given during 48 hours from

the fluid model; multiplying that number by 93/129; and then dividing the result by the mean number of targets that would be nominated in 48 hours. The bold entry corresponds to the fraction of targets for which there is command FWR for the parameters determined from FBE F data. The arrival rates are 0.5 times and 2 times the base arrival rate of 3.67 targets nominated per hour. The mean service times are 0.5 times and 2 times the base mean service time of 0.27 hours.

Fraction of Targets for which there is a Command Fire When Ready

		Nomination rate λ(tgts per hour)		
		1.83	**3.67**	7.36
Mean	0.17	0.68	0.66	0.58
service time	**0.27**	0.62	**0.53**	0.33
m_E (hrs)	0.54	0.47	0.31	0.17

Table 2

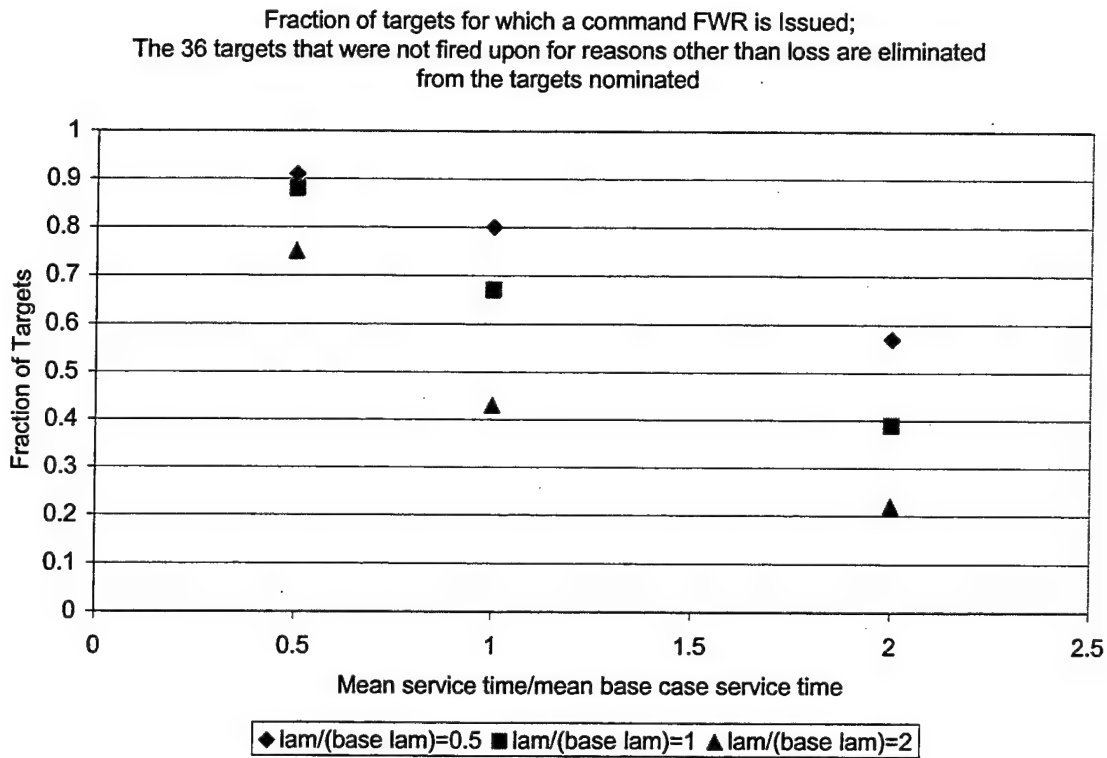A display of the fraction of targets for which a command of FWR is issued from Table 2 appears as Figure 4.

Fraction of targets for which a command FWR is issued.
The 36 targets that were not fired upon for reasons other than deficiency in time,
resources, etc remain in the system until command
FWR could have been given
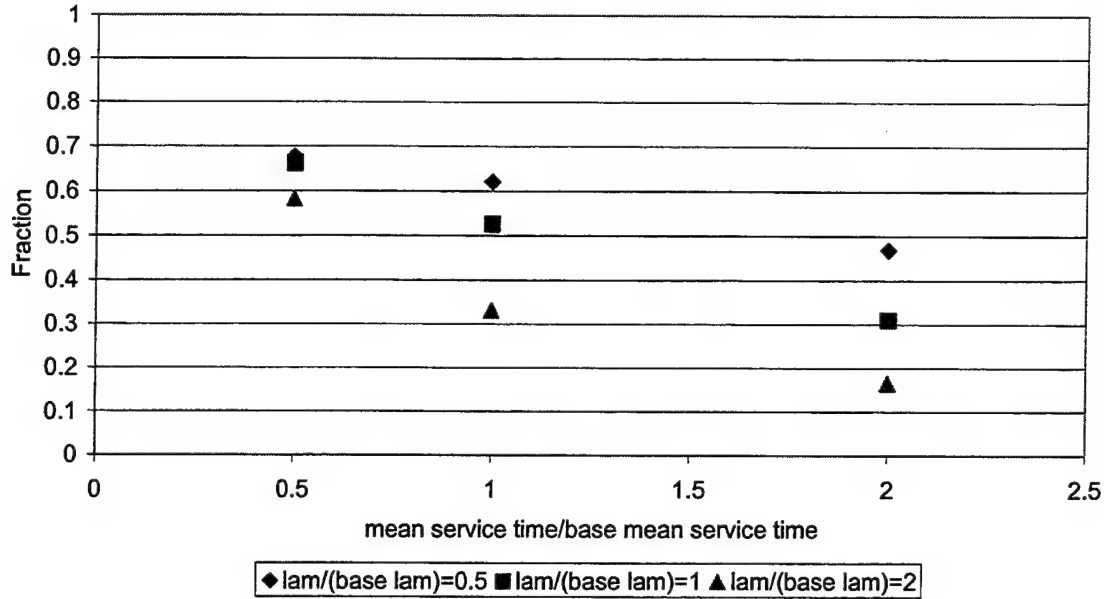
Figure 4

(e) Model III

We are assuming that 176-36=140 targets actually enter the CP for processing. This results in a constant arrival rate of 140/48=2.92 targets nominated per hour for the 48 hour period. We are assuming the command FWR is given for 93 targets out of the 140 targets nominated. The fluid model shows that if the mean time between target nomination and the command FWR is $W = 0.79$ hours and 93 commands could be given in the 48 hour period, then the mean target loss time, $(1/v)$, is about 2.4 hours and the mean service time by the central processor (LAWS and JTW) is about 0.35 hours $\approx$ 21 minutes, "on the average". Note again that this is an unrealistically optimistic case.

(e.1) AOOA: Sensitivity to Nomination Rate and Mean Service Time Variations

The table below presents the fraction of targets for which there is a command to FWR as the arrival rate and mean service time varies. The fraction is obtained by computing the mean number of targets for which the command FWR would have been given during 48 hours from

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the fluid model and dividing by the mean number of targets nominated during the 48 hour period. The bold entry corresponds to the fraction of targets for which there is command FWR for the parameters determined for the base case parameters. The arrival rates are 0.5 times and 2 times the base arrival rate of 2.92 targets nominated per hour. The mean service times are 0.5 times and 2 times the base mean service time of 0.35 hours. Fraction of targets for which there is a command fire when ready.

Fraction of Targets for which there is a Command Fire When Ready

| | | Nomination rate λ(tgts per hour) | | |
		1.46	**2.92**	5.82
Mean	0.14	0.91	0.88	0.75
service time	**0.27**	0.80	**0.67**	0.43
m_E (hrs)	0.54	0.57	0.39	0.22

Table 3

A display of the fraction of targets for which a command of FWR is issued from Table 3 appears as Figure 5.

Fraction of targets for which a command FWR is Issued;
The 36 targets that were not fired upon for reasons other than loss are eliminated
from the targets nominated

Figure 5

(f) Conclusions for This Example

A comparison of Tables 1, 2, and 3 and Figures 3, 4, and 5 displays the effect that the presence of the 36 targets which were not fired upon because of reasons other than deficiency in time, etc. can have on the performance of the CP. In Model II whose results are displayed in Table 2 and Figure 4, these targets remain in the system until the stage in which a command FWR would have been given, but are only then removed. In Model I whose results are displayed in Table 1 and Figure 3, these targets are subject to a loss mechanism while in service and so are removed from the system before the command FWR would have been given; thus in Model I these targets consume less CP resource. In Model III these targets are removed from the system at the time they are nominated and so consume no resources. The results show that the amount of CP resources that these 36 targets consume has a large effect on the ability to fire missions against time critical targets. The fraction of targets for which a

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command to FWR is the largest is that for Model III in which the targets consume no CP resources. Thus it is important for the CP to identify these targets as early as possible and remove them from consideration.

In summary,

(1) A simple BAT/IW-style fluid model can be quantitatively/numerically specified by using FBE Foxtrot data. Note that point estimates of basic rate parameters differ depending on how ineligible targets are treated: as in Model I, if mean CP service time is halved, the estimated FWR rate increases from 0.53 to 0.79 (49%), while in Model II it increases from 0.53 to 0.66 (25%). In Model III the removal of the ineligible targets before they enter the CP results in greater estimated FWR rates than either of the other two models. In Model III, The fraction of targets for which for the command FWR is 0.67 for the base case as compared to 0.53 for the other models.

(2) The *response* or MOE (fraction of nominated targets actually targeted) to variations in Red challenge (*roughly* the value of Nomination rate, λ) and Blue response capability (*roughly* the value of CP Mean Service Time, $1/\mu$) can *easily* be calculated, either *via* formula using a hand-held calculator, or simple Visual Basic-Excel programs already available. See Figures 3, 4 and 5.

4. PROPOSED EXTENSIONS AND FURTHER APPLICATIONS

The above models can be extended in various ways that will support operations analysis and system element tradeoffs.

(a) Exercise the current model for different arrival (here nomination) rates (and especially surge patterns, that reach the beginning of the current CP stage), and/or with different CP mean service times (involving human actions such as mensuration by JTW and weapon-target pairing by LAWS). *Expand the scope* of the present CP stages to include previous and subsequent stages!

The analysis and models must be extended to account for the availability of more than one/a single CP (JTW-LAWS). One way is to use dynamic sectorization, but there may be others, such as dynamic spatial sectorization by Blue weapon platform types (missiles and gunnery, *vs.* manned a/c *vs.* unmanned a/c). Apply to later/future FBE's data.

(b) Target images (*potential* targets) will not be of the same/similar types of platforms or other assets; e.g. they will have different mobility characteristics. Confusion / uncertainty between target types can realistically occur, and will be modeled; see original BAT/IW, Gaver and Jacobs (2000). It will be useful to extend the present analysis to examine mixtures of target types. Implications should motivate more specific observed/operational data collection. The effect of decoys is a case in point, especially when there is an assumed/known probability of correct classification (probability less than one); it will be desirable to plan to gather data that allows estimation of "confusion probabilities".

(c) Target images (potential targets) must be prioritized for CP service by *perceived* type. This is an uncertain process that can be analyzed. An objective could be to supply an automated decision aid to assist (not replace) human weaponeering.

(d) Consider, model, and analyze "flat" or "parallel-processing" architectures to replace the "vertical Central Processor (CP)" now (2000) in use. This, together with densely spaced small/local sensors, can *potentially* reduce response time and hence *potentially* greatly increase target prosecution rate, and again *potentially* increase target kill rate. It is in the spirit of Network-Centric Warfare; see Cebrowski and Garstka (1998), Alberts, Garstka and Stein (1998).

(e) All of the above can be analyzed at higher resolution, and stochastically (as always, using some basic assumptions, which it would be desirable to approximately verify from real data) by using more detailed simulation models such as NSS (Metron) and SEAS (Aerospace). It would be of interest to compare results with ours, later subject to (a), (b), and (c) above.

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APPENDIX A – A CENTRAL-PROCESSOR (C-P) MODEL

Let

$C(t)$ = the number of targets waiting for or being served by the Central Processor (CP)

$N(t)$ = the number of targets that complete processing during time $(0,t]$

Let

μ_E = the rate of processing time (=1/mE where mE is the mean time to process a possible target; it includes target mensuration and weapon assignment)

v_C = loss rate per detected target while being processed to a shooter

$$\frac{dC(t)}{dt} = \underbrace{\lambda(t)}_{\text{Total arrival rate (with feedback)}} - \underbrace{\mu_E \frac{C(t)}{1+C(t)}}_{\text{CP service rate}} - \underbrace{v_C C(t)}_{\text{CP loss rate}} \qquad (A.1)$$

$$\frac{dN(t)}{dt} = \underbrace{\mu_E \frac{C(t)}{1+C(t)}}_{\text{CP service rate}} \qquad (A.2)$$

Note that the term $\dfrac{C(t)}{1+C(t)}$ represents the saturability of the central processor: it cannot "work faster" than at rate μ_E; if several parallel facilities were available it would tend to behave similarly, but at rate = # of facilities*μ_E. See Gaver and Jacobs (2000), which describes the BAT/IW model. The term $v_C C(t)$ represents the rate at which enqueued potential targets are lost by the central processor. Such "losses" may occur because (a) some targets physically leave the region covered, or hide, or (b) track is lost because of load on the processor.

Little's formula, $C = \lambda W$, is used to rewrite equation (A.1) as an equation for the total time a target is in Central Processing; cf. Ross (1997). Let $W(t)$ be the time spent waiting and being served by targets in the central processor at time t.

$$\lambda(t)\frac{dW(t)}{dt} + \left[\frac{d}{dt}\lambda(t)\right]W(t) = \underbrace{\lambda(t)}_{\substack{\text{Total arrival rate}\\\text{(with feedback)}}} - \mu_E \underbrace{\frac{\lambda(t)W(t)}{1+\lambda(t)W(t)}}_{\text{CP service rate}} - \underbrace{v_C\lambda(t)W(t)}_{\text{CP loss rate}} \quad \text{(A.3)}$$

Dividing both sides by $\lambda(t)$,

$$\frac{dW(t)}{dt} + \frac{1}{\lambda(t)}\left[\frac{d}{dt}\lambda(t)\right]W(t) = 1 - \mu_E \underbrace{\frac{W(t)}{1+\lambda(t)W(t)}}_{\text{CP service rate}} - \underbrace{v_C W(t)}_{\text{CP loss rate}}$$

If steady-state or statistical equilibrium is assumed then $\dfrac{dW(t)}{dt} = 0$ (we must assume $\lambda(t) = \lambda$, a constant). Putting $W(t) = W$ and setting the LHS equal to 0 results in

$$0 = 1 - \mu_E \frac{W}{1+\lambda W} - v_C W \quad \text{(A.4)}$$

Solving for the service rate μ_E

$$\boxed{\mu_E = [1+\lambda W][1 - v_C W]/W} \quad \text{(A.5)}$$

This gives a simple estimate of service rate, given W, the mean time that a target (image) actually achieves the command Fire When Ready. This answer will typically agree well with the time-dependent calculation described earlier (starting with no target images present) if traffic is not too heavy.

Use of such backward inference seems unavoidable, starting from the FBE numbers available.

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